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Rectification by Open Arcs

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RECTIFICATION BY OPEN ARCS

BY

ARCHIBALD BEEBE VAN DEUSEN

B. S. University of Illinois, 1912

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Archibald Beebe Van Deusen

ENTITLED Rectification by Open Arcs.

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Science in Electrical Engineering.

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RECTIFICATION BY OPEN ARCS.

I. INTRODUCTION.

This thesis is a continuation of the thesis prepared by the author for the Bachelors degree in 1912, entitled, "Rectification of Alternating Currents By Means of a Carbon Arc." A brief review of the fundamental points of the previous thesis follows:-

A new method of rectification as suggested by Dr. Steinmetz * was partially investigated. This was rectification by means of a direct current arc. It was assumed on the authority of Dr. Steinmetz * and Mrs. Ayrton ** that the vapor stream of a direct current arc is an unidirectional conductor. This means that such a vapor stream will conduct electricity in one direction but not in the reverse. If a portion of this stream is included in an alternating current circuit, one half

* Steinmetz. Radiation Light and Illumination. Page 113.

** Ayrton. The Electric Arc. Page 70.

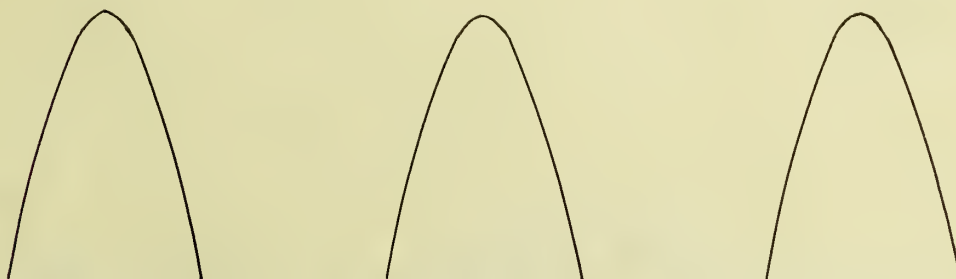


Figure 1

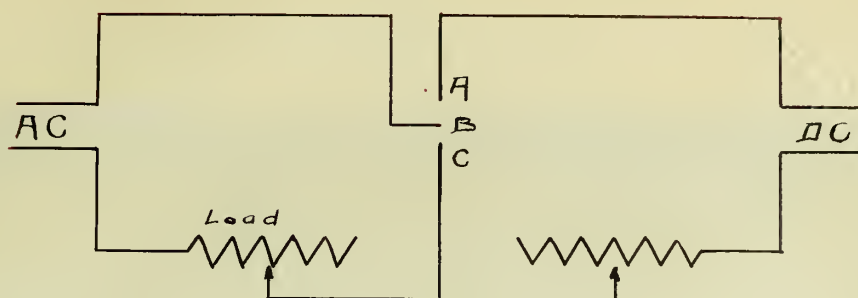
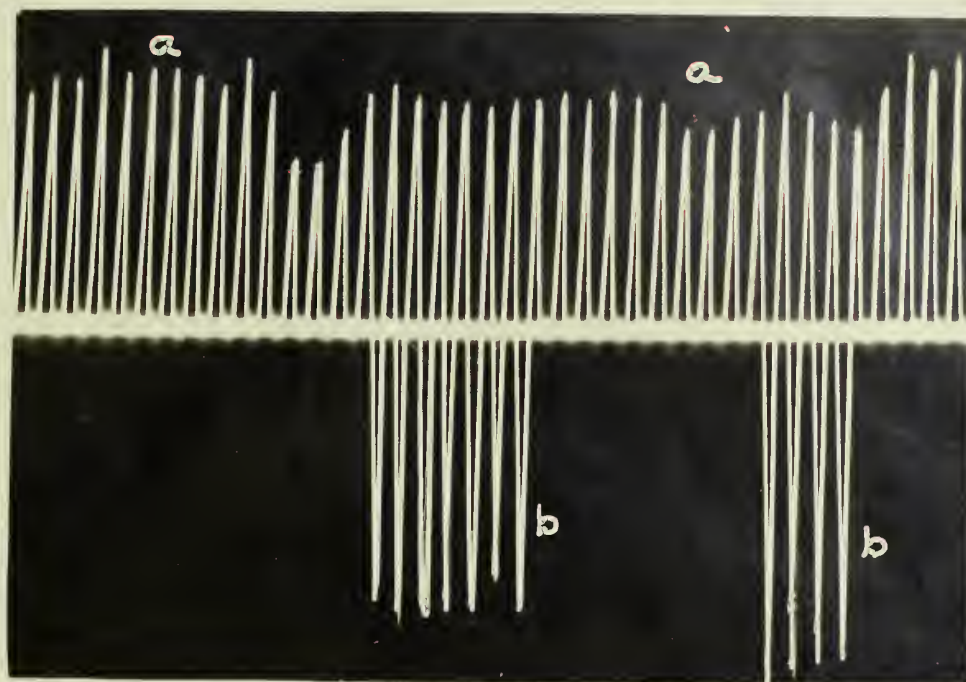


Figure 2

of the current wave will be able to pass thru while the other half will be suppressed. The result will be a pulsating direct current as is shown in Fig. 1. A diagram of the connections necessary to accomplish this is shown in Fig. 2. A direct current arc was maintained between the main electrodes A and C. A third or rectifying electrode (B) was inserted in the arc stream so that a part of the arc stream (B C) was included in the alternating current circuit. Only one half of the current wave was able to flow in this circuit, and hence rectification was accomplished.

There was found to be a limit on both the current and voltage rectified. As the voltage of the rectified circuit was increased the potential difference between B and C increased. When this potential difference was small the half wave of rectified current flowed in this circuit, as shown in oscillogram 2 and at a in oscillogram 1. When the potential difference became too great, rectification ceased, since an alternating current arc was started and maintained between the terminals B and C. This action was aided by the presence of the hot



Oscillogram 1.

vapor stream between these terminals. When this arc occurred an alternating current flowed in the load, as shown at b oscillogram 1. This has been termed the breakdown of rectification, and the voltage at which it occurred the point of breakdown. In order to raise this point of breakdown it was decided that the rectifying terminal should be cooled.

Rectification also ceased when the current in the load was increased above a certain value, for one of two reasons. First:- Since the rectified and the direct current circuits were in parallel thru the rectifying part of the arc (B C Fig. 2), this part of the direct current arc was short circuited by the rectifying circuit. When the resistance of

this short circuit was high it had no detrimental effect on the rectification. This means that the current in the rectified circuit was necessarily small. If, in order to rectify greater power the current in the load was increased, the resistance of the load was necessarily decreased. Thus the resistance of the short circuit first mentioned was decreased and finally became less than that of the rectifying part of the arc (B C Fig. 2) which, on account of its negative characteristic, was consequently extinguished. This occurred if the main terminal used was the anode. * Second: If the main terminal used was the cathode, the arc was not extinguished but the large rectified current leaving the center electrode heated it to such an extent that the point of breakdown was materially lowered. Thus it is seen at the outset that rectification by this method is very limited.

In the 1912 thesis the investigations were carried on with comparatively high currents and low voltages in both the alternating and direct current circuits. This produced great heating which was very detrimental to the operation. In the present investigations high voltages and low currents were used to partly overcome this difficulty.

The problem has now been narrowed down to an investigation of the exact limitations of this method of rectification, and a corollary problem concerning the mechanical operation of the rectifier. It was, of course, necessary to solve this latter problem before the former could be taken up, hence the

* Steinmetz. Radiation Light and Illumination. Page 111.

mechanical operation of the rectifier will be considered next.

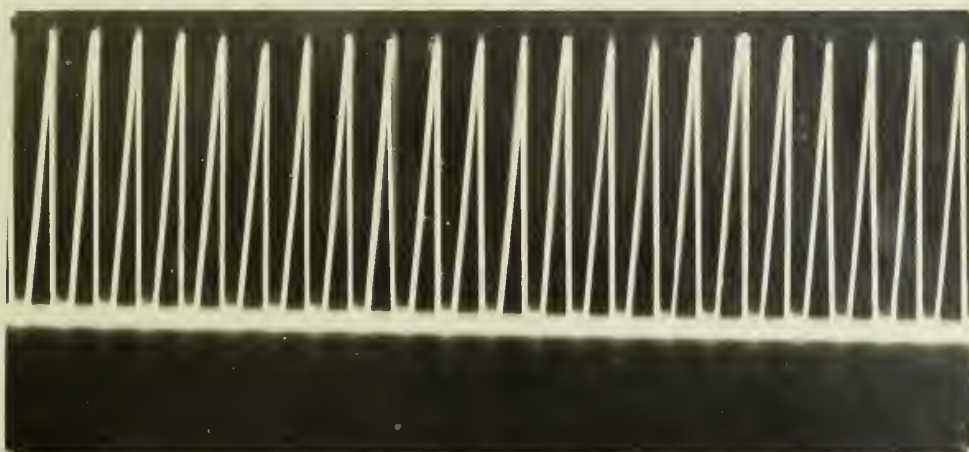
II MECHANICAL CONSIDERATIONS OF THE DIRECT CURRENT ARC RECTIFIER.

The arc mechanism must obviously be such that an arc can be conveniently struck, and maintained between the main electrodes, and be as nearly steady as possible. This last requirement is very important since the rectifying terminal should make connection with the arc at the very center of the arc stream, in order to obtain the highest efficiency. It is obvious that if the arc stream moves about; the rectifying terminal, which is stationary, will be in the center only occasionally and therefore the rectified current, which depends on the ionic density of the stream, will vary greatly from time to time. To illustrate this, the rectification of a full half wave, when the terminal touches the core, is shown in oscillogram 2 (#7); whereas, the rectification with "a wandering" arc is shown at a in oscillogram 1, (#8). The preliminary work done in 1912 proved rather conclusively that a vertical arc was not satisfactory.

This year, therefore, a horizontal arc was used. It is well known that an electric arc placed in a magnetic field obeys the same laws as a wire carrying current in a magnetic field. The rectifying arc stream was therefore placed in a constant and uniform magnetic field. The direction of this field was such as to force the stream downward. The magnetic force balanced the tendency of the arc to rise and extinguish

itself. The arc was enclosed in an asbestos chimney, open both at the top and bottom. A partition was placed in the chimney directly below, and parallel to the stream. This partition directed the upward draft along the side walls, and kept the arc from wandering laterally. This gave a fairly steady arc stream, and solved many of the problems connected with the rectifier.

In order to strike the arc it was necessary to have one terminal movable in the horizontal direction. This made it possible to have the rectifying electrode (B Fig. 2) and one of the main electrodes (B Fig. 2) fixed, which simplified the cooling problem very much. These two electrodes were made of copper pipe and cooled with water. The third terminal was placed slightly above the line of travel of the movable main terminal. By regulating the strength of the magnetic field and the draft, the arc stream was allowed to bend upward slightly, until it made good contact with the rectifying electrode.



Oscillogram 2.

The material used in the second main electrode was impregnated carbon, which gave a large arc stream. With an arc at 160 volts and 4-5 amperes a very steady condition was obtained. With an arc of 200 volts the condition was very unstable. This, however, was probably due to faults of the apparatus. The 200 volt arc was so long that it was partly outside the magnetic field. Furthermore at this point the generators which supplied direct current could not be kept at constant voltage. It is not surprising therefore that the arc proved unmanageable. An arc consuming 100 volts and 4.5 amperes was so short that for purely mechanical reasons the third terminal could not be introduced. Hence, it is concluded that this method of arc stream control would probably be satisfactory in all cases if the apparatus were properly designed.

III THEORY AND PERFORMANCE OF RECTIFICATION BY A COOLED--COPPER--CARBON DIRECT CURRENT ARC.

As a result of considerable experimental work the mechanical operation of the arc rectifier has now been improved to such a point that the electrical side of the problem may be examined. This discussion will then include: first, observations from tests; and second, the theory, which will explain all observed facts, which will be consistent in itself, and in accord with known electrical laws.

It is evident at a glance that the arc itself is the crucial point in this investigation. Here are a large number of factors which may vary; such as, current and voltage in both the arc and the load, temperature and material of the electrodes. Not all of these factors may vary independently. There is undoubtedly a relation between the arc current, voltage and length. The relation between current and voltage in the rectified circuit must be according to Ohms law in its most general form. Hence it is not always possible to vary a given factor and hold the rest constant. It is, however, possible to vary any group of factors by varying one of them, and to study the effect of this variation on the phenomena in general.

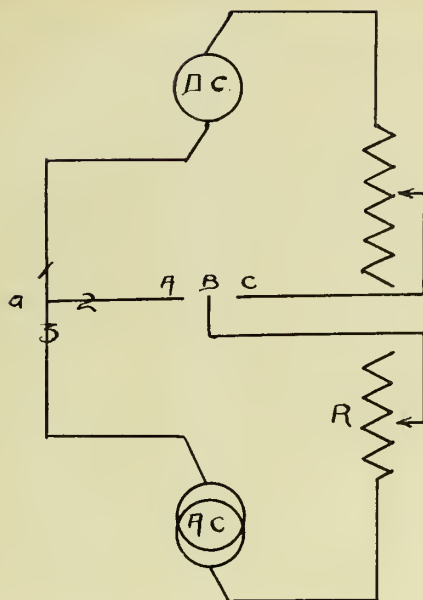


Figure 3.

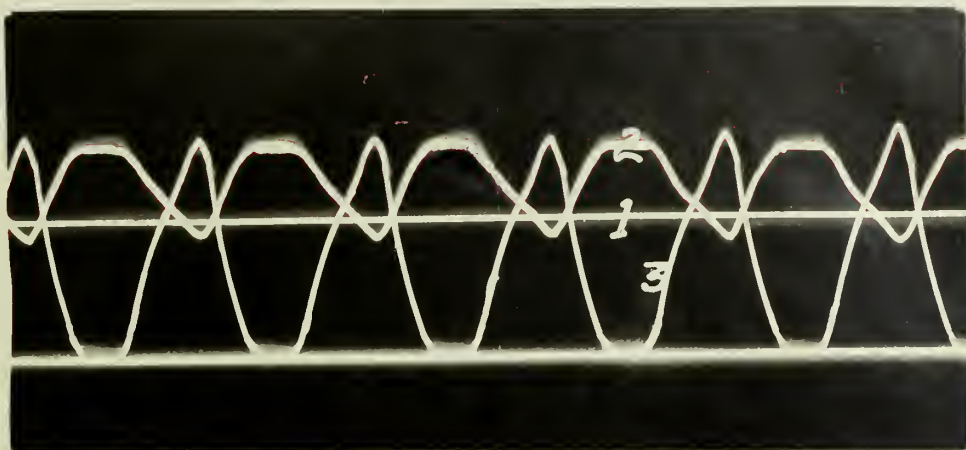
Figure 3 is a diagram of the circuits in the rectifier omitting the instruments etc. There are two main circuits, the upper or direct current circuit which supplies the current for the rectifying arc between the main terminal A and C; and the lower or rectifying circuit which contains the pulsating direct current. These two circuits are in parallel thru the length aAB. Due to the arc stream there is a direct current difference of potential between A and B which may be sufficient to send direct current thru the lower circuit. If the alternating current can flow from B to C, it may be possible to have alternating current in the upper arc circuit. In order to study these currents the three elements of an oscillograph were inserted in the circuits across shunts at 1, 2 and 3, thus indicating the currents in the three possible paths. These shunts were neither uniform nor callibrated, hence their purpose is to give only the shapes of the waves.

The first examination of the currents in the rectifier demonstrated the necessity of their thorough investigation. This investigation was made as follows:

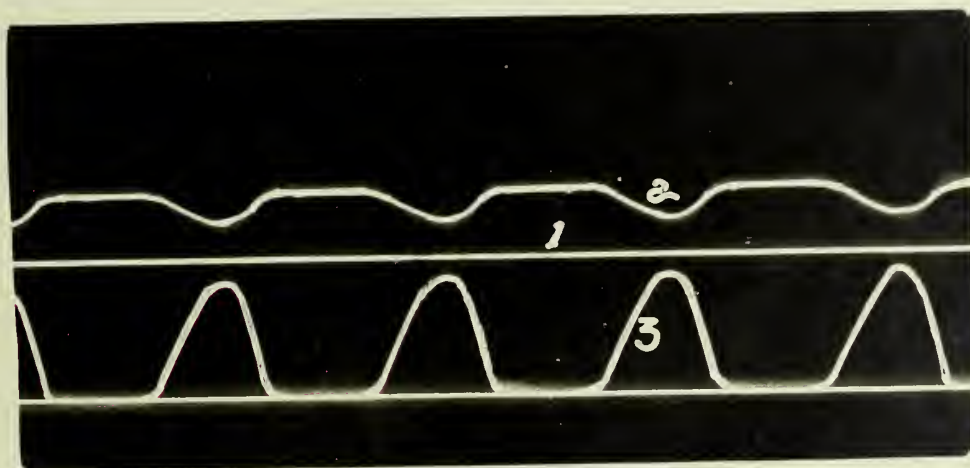
- 1- With the oscillograph as has been mentioned.
- 2- With direct current in the lower circuit.
- 3- With a special third terminal.

The results of these experiments made it necessary to give up the old theory of the unidirectional conductive nature of the direct current arc stream as fallacious. A new hypothesis was formed to account for the rectification which may be termed, the hypothesis of the cathodic action of a vapor giving terminal. These experiments and deductions will now be given in full.

With the connections as shown in Figure 3, Oscillogram 3 (#2) was taken, from which the following conclusions can be drawn. Wave 1 being an absolutely straight line shows that there is no alternating current in the upper or arc circuit. Wave 3 shows the pulsating direct current. It is observed that the spaces on the ground line under the loops are much larger than those between the loops. This is due to the fact that some direct current from the upper circuit, as was mentioned in a preceding paragraph, has displaced the whole alternating wave upwards. Wave 2 must be the sum of waves 1 and 3, according to Kirchhoff's law. The oscillogram shows that the direct current deflection is upwards, while that of the rectified current is downwards, hence these two currents must be following in opposite directions, and one of them must be considered



Oscillogram 3.



Oscillogram 4.

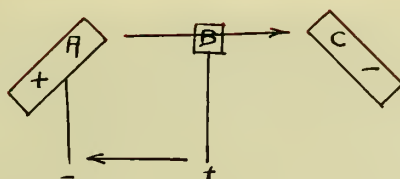
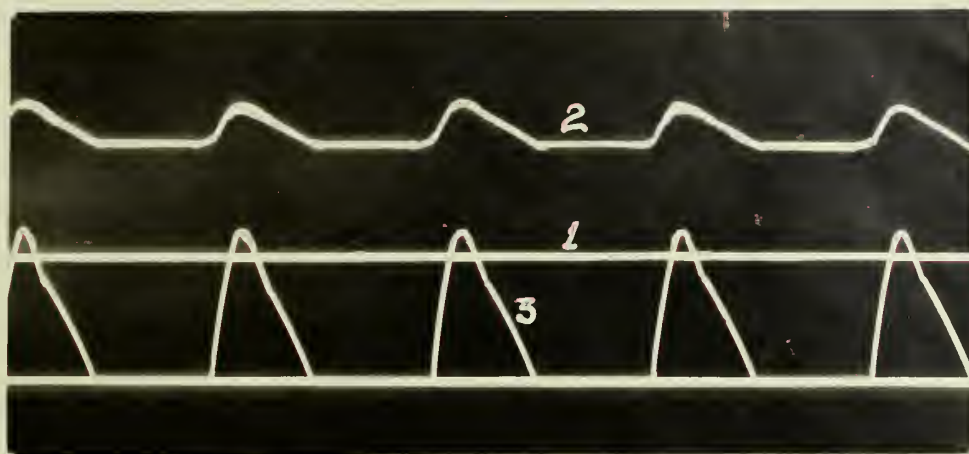


Figure 4.

negative. Figure 4 represents the three terminals of the arc, A, B and C. The polarity of the main terminals A and C is shown. This was observed when the oscillogram was taken. The upper arrow, therefore, represents the direction of the current in the main arc. From the observations just made regarding the oscillograph deflections in wave 2, it is evident that the rectified current is going in the opposite direction. This is indicated by the lower arrow, which necessitates the polarity of A and B to be as shown, in respect to the lower circuit. Oscillogram 4 is exactly the same as Oscillogram 3, except that R, Figure 3, has been increased. This decreased the effect of the potential difference across A B, due to the arc stream, and hence decreased the true direct current in the lower circuit. As is expected the spaces between and under the loops of wave 3 are nearly equal.



Oscillogram 5.

The direction of the current in the arc was now reversed and Oscillogram 5 was taken. All connections remained as for Oscillograms 3 and 4, except that the oscillograph leads for waves 1 and 2 were reversed to throw these waves on the same side of the ground line as wave 3. Waves 1 and 3 are similar to those in Oscillograms 3 and 4 and the same conclusions are drawn. Wave 2 is markedly different. Here the deflections due to the direct and rectified currents are both upward. Therefore these two currents are in the same direction. The polarity of the terminals and the current directions were found as before, and are shown in Figure 5.

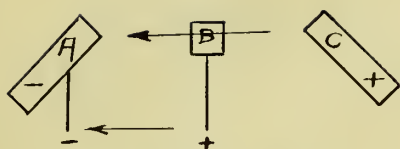


Figure 5

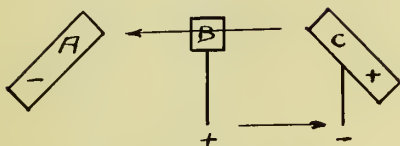


Figure 7

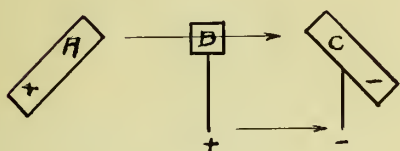


Figure 8a

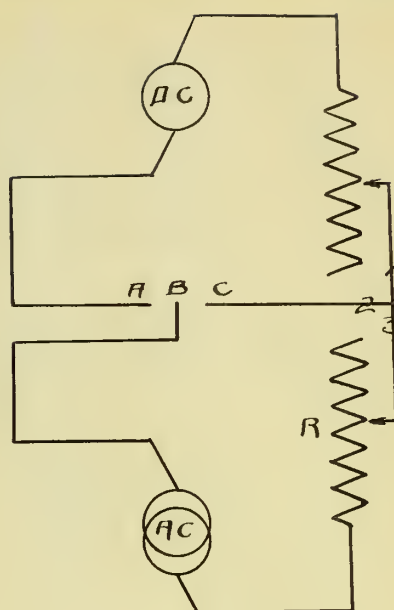


Figure 6.

In the previous oscillograms A and B were the rectifying terminals. A is cooled copper. Terminals B and C were now used, as shown in Figure 6. B is carbon. Two oscillograms were taken with these connections, the oscillograph shunts being placed at 1, 2 and 3, and the arc current being reversed for one of them. The first gave waves exactly similar to those in Oscillogram 4. The polarities and current directions must be those shown in Figure 7. The second oscillogram was similar to Oscillogram 5, which gave the polarities and current directions shown in Figure 8a. Figures 4 and 7 show that the rectified current is flowing against the arc current. Figures 5 and 8a show that the rectified and arc currents are flowing in the same direction. The only possible explanation of this is that the rectified current can flow in either direction thru the arc stream. This gives the first and most definite proof against

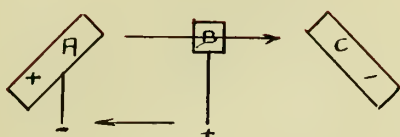


Figure 8

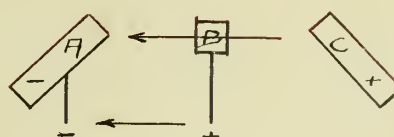


Figure 10

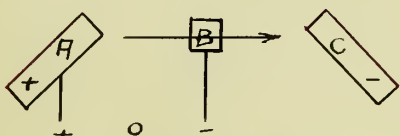


Figure 9

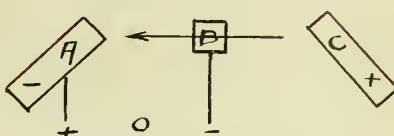


Figure 11

the principle of the unidirectional conductive character of the direct current arc stream.

To further study the direction of conduction in the arc stream, direct current was impressed on the rectifying terminals A and B. The connections used are shown in Fig. 3, with direct current substituted for the alternating in the lower circuit. The polarities of the upper and lower circuits were now arranged as shown in Figs. 8, 9, 10 & 11. In the experiments corresponding to Figs. 8 & 10 current flowed in the lower circuit. In the experiments corresponding to Figs. 9 & 11 no current flowed in the lower circuit, although the voltage across A B due to the lower circuit was much larger than that due to the arc.

The above experiments were repeated using the connec-

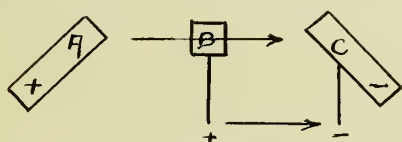


Figure 12

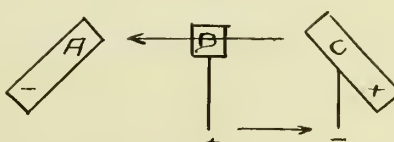


Figure 14

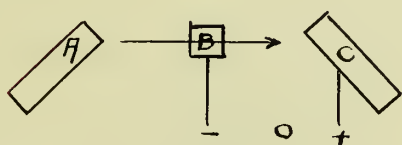


Figure 13

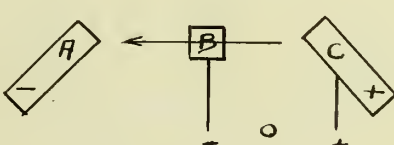


Figure 15

tions shown in Figure 6, with direct current in the lower circuit. Figures 12, 13, 14, and 15 show the combinations of polarities used. Current flowed in the lower direct current circuit in 12 and 14 but not in 13 and 15. The directions of the currents in the eight Figures 8 - 15 are shown by the arrows. In Figures 8 and 14 the current from the lower circuit flowed against that from the upper or arc circuit. In Figures 10 and 12 these two currents flowed in the same direction. Again the conclusion is that current may flow either way thru the arc stream, and a second proof is established against the unidirectional conductive nature of the direct current arc.

The third or rectifying terminal used thus far was a water cooled copper tube. This was now replaced by a carbon plate, the plane of which was perpendicular to the axis of the arc. The direct current arc was formed thru this plate so that it became really two arcs, one on each side of the plate. The connections were made as per Figure 3. An examination of the current in the lower circuit showed a full sine wave, with no rectification what so ever. Thus the current passed in either direction between the terminals A and B. The experiments described in the preceeding paragraph, using direct current in the lower circuit, were repeated and it was found possible to pass current between this kind of a third terminal and either of the main terminals in either direction. In this case there is a hot spot, either cathode or anode, on either end of the rectifying part of the arc, A B (Figure 3) or B C (Figure 6). This gives a third basis for concluding that the direct current

arc stream is not a unidirectional conductor, and hence the explanation of the phenomena of rectification by such an arc stream on this basis must be abandoned. Since, however, rectification has been accomplished it must have some logical theory. An examination of Figures 5 and 7 to 15 shows one point of similarity. The rectified current or that in the lower circuit always flows to the hot rectifying electrode, which is of course the main terminal. In every case in which it has been found possible to pass current thru the lower circuit (Figures 3 and 6), and thru a part of the arc stream the hot main terminal used is the cathode of the arc part of the lower circuit irrespective of whether it is the cathode or anode of the upper arc circuit.

It is well known that in conduction of electricity thru gasses, the conducting vapor comes from the cathode although the current flows to this terminal. When alternating current is impressed on the lower or rectifying circuit that member of the rectifying terminals which has a hot spot becomes the cathode of the rectified current. This is, of course, the rectifying terminal of the main arc. The rectified current here finds a hot spot from which it can start a vapor blast at moderate voltages. As the other terminal has no hot spot no vapor blast may start from here until the rectified voltage becomes so high that it breaks down the heated vapors between the terminals. The same action takes place in the case when direct current is impressed on the lower circuit. Thus at moderate voltages current may pass more easily to the hot terminal than away from it. When

the carbon plate is used as the center electrode, the current in the lower circuit has a hot terminal at either end of the included arc and hence may pass in either direction. This gives a logical and satisfactory explanation of the phenomena of rectification by means of a direct current arc.

The question of ^{the} effect of arc current, length and voltage on rectification is a difficult one to discuss, chiefly for two reasons; first, the difficulty of determining the point at which rectification ceases; and second, the interdependence of these quantities. The rectification always ceased by breaking down, rather than by the extinction of half the arc. * This point of breakdown was hard to determine. The oscillograph showed when the half wave was flowing and this was also easily noted by the increased readings of the meter in the rectified circuit. For low values of current and voltage in the rectified circuit, breakdown would occur during a few cycles at long intervals. These intervals became shorter as the current and voltage was increased until no rectification at all was obtained. For some direct current work, such as charging storage batteries, infrequent breakdown is allowable. With infrequent breakdown much greater rectified power can be obtained than with perfect rectification. The data taken was at the point where breakdown was infrequent, which may be termed the point of allowable breakdown. It is evident, however, that the selection of this point by the observer, under various

* See Page 3.

conditions and at various times, may differ greatly. Therefore although a great deal of data was taken only general conclusions can be drawn. For this reason and because of the great variation in the readings only a few are included in this thesis.

While the laboratory facilities limited the direct current to five amperes, and no tests were made with greater current than this in the arc, it seems evident that the power which can be rectified is in direct proportion to the direct current in the arc. This conclusion may also be reached from theoretical considerations. The arc stream conducts the current rectified. This current is carried by the ions in the arc stream; since these ions carry the arc current, the greater the arc current, the greater the number of ions and the better the conducting properties of the arc stream. The heating of the terminals is also a function of the arc current, and the cathodic action of the rectified current at the hot terminal is due to this action, hence the extent of rectification depends directly on this current. From this latter consideration it would be inferred that a hot carbon terminal would be the best for rectification. This conclusion was also very strongly verified by the data taken.

As far as could be ascertained the point of breakdown was very slightly affected by the distance between the rectifying electrodes. This is probably due to the presence of the vapor stream, which provides a good path for the current, when the rectified voltage has become high enough to cause

breakdown at the terminal. It was finally concluded that a distance of about half an inch between the nearest points of the rectifying terminals was best. In this case the total length of the arc stream was about nine tenths of an inch. With this arrangement of terminals and about five amperes flowing in the direct current arc the largest and most efficient rectification was obtained.

It has been shown that the action of the rectifier depends on the presence in the circuit of a hot and a cold terminal. It is inferred that the greater the temperature difference the more efficient the operation. The carbon crater gives the highest possible temperature. The rectifying terminal must be made of some material which will readily give up its heat to water passing thru it. As has been stated a thin copper tube was used in these experiments. A zinc tube was not obtainable but if it has been it is concluded that better rectification could have been obtained. This is due to the fact that zinc electrodes give a cold arc, the temperature being very much below that of carbon. Thus the rectified current leaving the zinc center terminal would not produce such high local heating, and breakdown of the rectification would not occur at as low a voltage as if copper were used. An experiment was made on the general heating of the copper terminals. The cooling water was cut down until only sufficient to prevent the consumption of the electrodes. The tubes became visibly hot, but no difference in the breakdown voltage could be ascertained.

Table 1 contains some typical readings which were obtained with the connections shown in Figure 16. The lengths are the distances between the nearest points of the terminals. This is not necessarily the length of the included arc, as has been shown. The load in the rectified circuit was noninductive hence $P = EI$. This was also proven experimentally.

Table 1.									
Rectified Circuit.			Arc Circuit			Total Length of Arc	Length of Rectifying Arc	Efficiency %	Polarity as Shown In
E	I	P _R	E	I	P _A				
200 volts	1.2 amps	240 watts	125 volts	4.7 amps	560 watts	1.31 in.	.56 in.	30	Fig. 4
335	.5	167	150	4.8	560	1.5	.56	22.9	
100	1.6	160	150	4.3	600	1.375	.42	21	Fig. 5
200	1.2	240	150	4.	600	1.375	.42	29.2	
280	1.3	364	150	4.5	640	1.375	.42	35	
380	.35	95	160	4.1	640	1.625	.67	12.9	
100	.86	86	170	4.	640	1.625	.56	11.8	Fig. 7
200	.8	160	150	4.1	580	1.375	.56	21.6	
100	.5	50	125	4.5	520	1.375	.42	8.8	Fig 8a

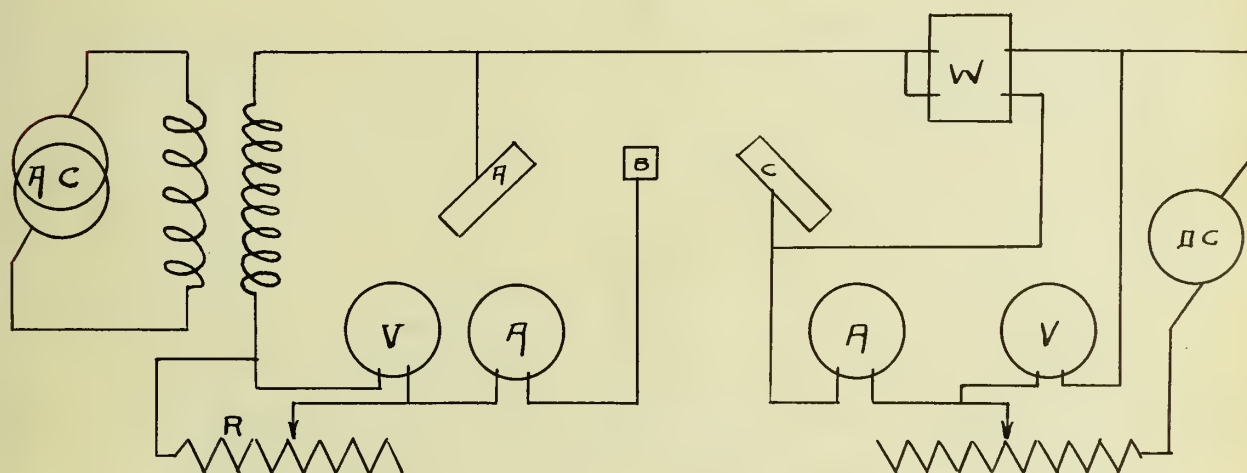
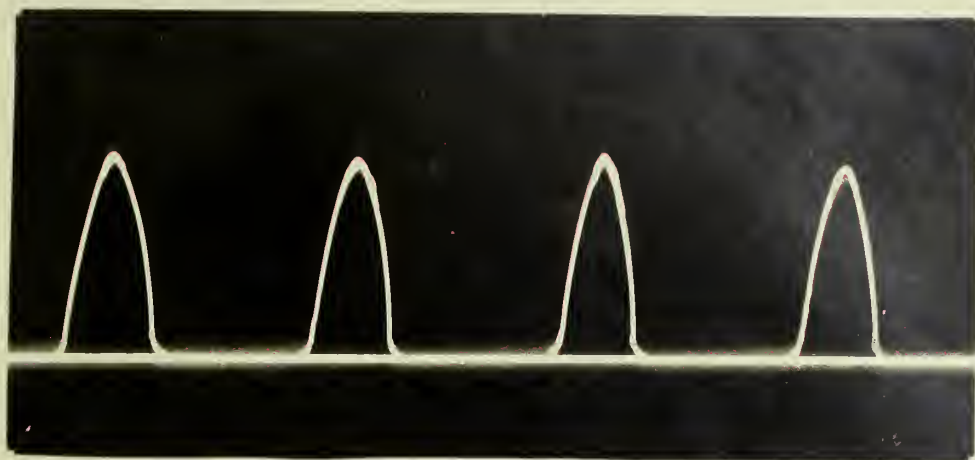


Figure 16.



Oscillogram 6.

IV THE ALTERNATING CURRENT ARC RECTIFIER.

From the study of the direct current rectifier, it is concluded that the principal requirement is a hot and a cold terminal in the alternating current circuit. These terminals must be connected by a vapor stream issuing from the hot member. Obviously it should be possible to produce these conditions with an alternating current arc. Figure 17 shows the first alternating current arc rectifier investigated. A and C are the hot carbon terminals of an alternating current arc. B is a cooled copper terminal and hence will always be positive with respect to A and C for any current flowing thru R. It is evident that for one half of the wave B will be positive with respect to A, and for the other half it will be positive with respect to C, hence both halves of the wave will flow thru R in the same direction, and a current as shown in

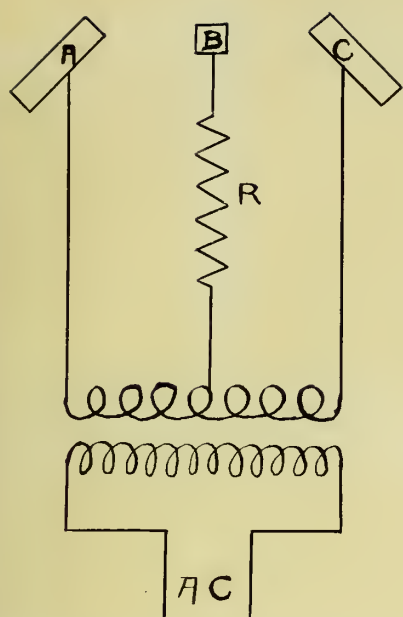


Figure 17.

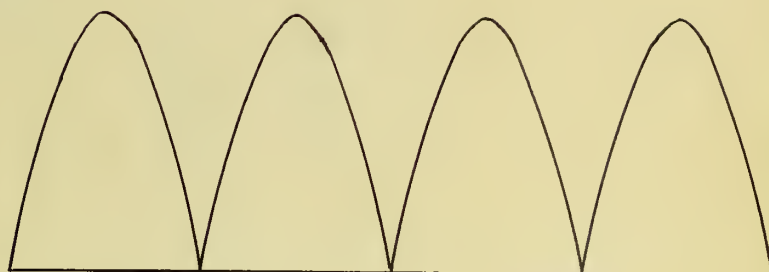


Figure 18.

Figure 18 will be obtained. With the arc extinguished the voltage across A C was about 400, but with the arc burning it was only about 150. Thus the drop across A B or B C was, at best, only about 75 volts. This was not sufficient to break down the hot vapors in either direction and no rectification was obtained.

In these experiments a water cooled hood or roof was used to prevent the arc blowing out. This proved fairly satisfactory and the hood was used as the third terminal B (Figures 17 and 19.) To overcome the difficulty explained in the preceeding paragraph, the connections as shown in Figure 19 were evolved. This gives the full transformer voltage across A B, which was about 400. It would be expected that a half wave of rectified current should flow in R. This was attempted experimentally and proved successful. Oscillogram 6

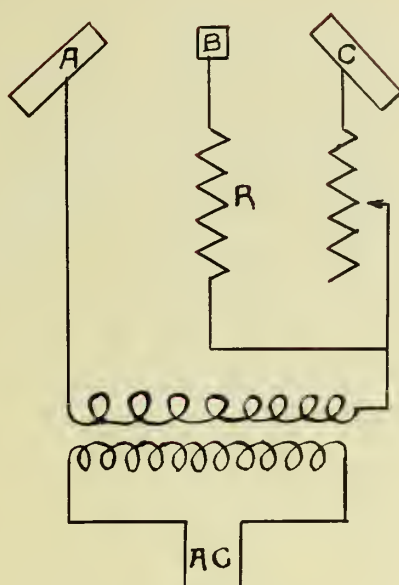


Figure 19.

shows the half wave obtained. The length of the arc and the position of the carbons below the hood was apparently very important. The heavy arc stream from the impregnated carbons used, did not seem to make very good contact with the hood, and it was concluded that some electrodes giving a thin dense arc stream should be used for the main arc. With the crude rectifier devised about 800 watts were consumed in the arc; and about 80 watts were rectified and consumed in the load. This gave an efficiency of about 10% at the very first of the experimental investigations.

The so called direct current arc rectifier consumes direct more current than it rectifies, and hence has no real efficiency as a rectifier. The rectifier just described however, actually delivers pulsating direct current, with an input of alternating current only. Thus it is a rectifier in the true sense of the word.

The apparatus is very simple, and omitting the transformer, costs very little. Enough current has already been rectified to charge a small storage battery and it appears as though a much greater rectified current could be obtained. This rectifier opens a very interesting field of research, and it is a great disappointment to the author that the allotted time for this thesis expired before it could be thoroughly investigated.

V CONCLUSION.

Rectification of alternating current was found to depend on the presence of two terminals in the circuit, one of which gives off a vapor stream and is very much hotter than the other. In the direct current arc rectifiers this hot terminal and the consequent vapor stream are produced by the use of a direct current arc. From the investigations made it is concluded that this rectifier is not an economic possibility, as more direct current was expended in the arc than was rectified. Since, however, it is possible to produce this hot terminal and vapor stream by using an alternating current arc and since rectification can be accomplished by such an arc, a new simple and cheap rectifier has been produced, which gives a pulsating direct current with an input of alternating current alone. This rectifier was devised when the allotted time for this thesis was practically gone, therefore further investigations were impossible. Even though the first efficiency obtained was low, great possibilities are apparent if this method is perfected, and a further study along these lines may go far towards solving the problem of rectification.





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